



Fermilab

TM-1177
2700.000

OPERATING MANUAL AND DESIGN REPORT OF A 5000A QUENCH SWITCH
FOR ENERGY DOUBLER MAGNETS IN EXPERIMENTAL AREA BEAMLINES

A. T. Visser

April 1983

TABLE OF CONTENTS

<u>CHAPTER</u>		<u>PAGE</u>
1	LISTING OF DRAWINGS.....	1
2	GENERAL SYSTEM DESCRIPTION AND PARAMETERS.....	4
3	DESCRIPTION OF SUBSYSTEMS.....	7
	3.1 Ground Fault Detector.....	7
	3.2 Magnet Quench Imbalance Detector.....	8
	3.3 Run SCR Gate Control.....	9
	3.4 Lead Overvoltage Protection.....	10
	3.5 Dump Charge Control.....	11
	3.6 Interlocks.....	13
	3.7 First Fault Detector.....	14
	3.8 Heater Control.....	15
	3.9 Redundant Failure Detector.....	16
	3.10 Control Power.....	17
	3.11 Summary.....	17
4	PERSONNEL SAFETY.....	18
5	SYSTEM TRIP SETTINGS.....	20
	5.1 Magnet Imbalance Detector..... (Quench Detector)	20
	5.2 Lead Overvoltage.....	23
	5.3 Dump Charge.....	25
	5.4 Heaters.....	26
	5.5 D.C. Overcurrent.....	26

TABLE OF CONTENTS

<u>CHAPTER</u>		<u>PAGE</u>
6	FIRST START UP AND SYSTEM CHECKS.....	27
	6.1 Wiring.....	27
	6.2 Megger.....	27
	6.3 System Tests.....	27
	6.4 Start Low Current Run.....	28
7	DESIGN CALCULATIONS.....	30
	7.1 5000A Quench Switch Cooling Flow Estimates.....	31
	7.2 Calculate the Run SCR Operating Temperature.....	32
	7.3 Calculate the Heat Sink Temperature....	33
	7.4 Calculate the Cooling Flow Pressure Drop.	33
	7.5 Calculate the Dump SCR Operating Temperature.....	34
	7.6 Calculate the Dump Diode Operating Temperature.....	36
	7.7 Calculate the Size of the Dump Capacitor	37
	7.8 Design Current Balancing (Sharing) Resistors for 2-2500A SCR's in Parallel..	38
	7.9 Dump SCR di/dt Considerations.....	39
	7.10 Design of the Soaking Reactor to Limit Dump SCR di/dt < 200A/μ sec.....	40
8	MATERIAL COST ESTIMATE.....	47
9	ACKNOWLEDGEMENTS.....	48
10	REFERENCES.....	49

1. LISTING OF DRAWINGS

The following drawings show electrical, installation and assembly information used for the 5000A Quench Switch in Proton Enclosure "H".

<u>DRAWING NUMBER</u>	<u>TITLE</u>
	Quench protection encl."H" west bend-
2789-EC-172034-SH 1*	Electrical flow diagram.
2789-EC-172034-SH 2*	Ground fault detector.
2789-EC-172034-SH 3*	Quench imbalance detector.
2789-EC-172034-SH 4*	Run SCR gate control.
2789-EC-172034-SH 5*	Lead overvoltage window comparator with automatic load current compensation
2789-EC-172034-SH 6*	Dump cap. charge and control.
2789-EC-172034-SH 7*	Interlock summation, 12 channel.
2789-EC-172034-SH 8*	8 Channel first fault detector and gated pulse generator.
2789-EC-172034-SH 9*	Magnet control and heater wiring and interconnection.
2789-EC-172034-SH 10*	Heater firing control.
2789-EC-172034-SH 11*	4 Channel heater chassis assembly
2789-EC-172034-SH 12*	Heater chassis firing circuit and heater fault monitor.
2789-EC-172034-SH 13*	Redundant circuit failure detector.

<u>DRAWING NUMBER</u>	<u>TITLE</u>
	Quench protection encl."H" west bend-
2789-EC-172034-SH 14*	Control power, standby power.
2789-EC-172034-SH 15*	Nim crate assembly details.
2789-EC-172034-SH 16	Nim crate wiring, rear view.
2789-EC-172034-SH 17	Nim crate wiring, rear view.
2789-EC-172034-SH 18	Nim crate wiring, rear view.
2789-EC-172034-SH 19	Nim crate wiring, rear view.
2789-EC-172034-SH 20	Nim crate wiring, rear view.
2789-EC-172034-SH 21	Nim crate wiring, rear view.
2789-EC-172034-SH 22	Nim crate wiring, rear view.
2789-EC-172034-SH 23	Interconnection crate power supply, quench switch, dump resistor.
2789-EC-172034-SH 24	Interconnection-DC PS, crate, heater PS, dump P.S.
2789-EC-172034-SH 25*	Cable pulling plan.
2789-EC-172034-SH 26*	Relay rack wiring plan and AC distribution.
2789-EC-172034-SH 27	Layout of crate back connectors and cables.
2789-EC-172034-SH 28*	Electrical power single line, cooling and SCR mounting details.
2789-EC-172034-SH 29*	Interlock and trip flow diagram.

DRAWING NUMBERTITLE

	Quench protection encl."H" west bend-
2789-EC-172034-SH 30*	Summary of crate fault lights and terminal block assignment.
6004-EC-76806-Rev.B	5000A quench switch balancing resistor assembly.
6004-EB-76807	Alignment tool for 5000A balancing resistor, water cooled bus.
6004-EE-76811	5000A quench switch dump resistor for "H" (needs updating).
6004-EE-76807-Rev.A	5000A quench switch assembly
6004-EB-76813	5000A quench switch, SCR soaking reactor.
6004-EC-76805	Heat sink assembly, 5000A quench switch.

* These drawings are attached to this report.

2. GENERAL SYSTEM DESCRIPTION AND PARAMETERS

Refer to sheets 1, 28, 29, 30.

The cryogenic west bend in Proton's enclosure "H" consists of five 21' energy doubler magnets fed from a 5000A power supply via watercooled bus. The stored energy of the magnets will be dumped in a resistor R_D , when S_1 , S_2 , are shut off. Magnet heaters will be fired if S_1 , S_2 , fail to open (dump failure). These heaters are strictly used for backup protection. Sheet 29 shows the interlock flow diagram.

There are five distinct separate interconnected parts, which make up the complete system.

They are:

1. Magnets
2. DC magnet power supply
3. Quench switch assembly
4. Dump resistor assembly
5. Relay rack containing:
 - control electronics,
 - dump charge capacitors,
 - heater power supplies,
 - etc.

Only the magnets are located downstairs about 250 feet away from the other components. The installation at enclosure "H" is rated to handle 3800 ADC at about 1000V peak. The midpoint of the dump resistor is intentionally connected to ground via 200 Ω . All control wires are connected to the power system via 10 K Ω current limiting resistors and or isolating transformers and amplifiers. The conventional beamline power supply control system is adequate for remote computer control of the system. Additional switch status information is available at the relay rack (sheet 30).

The most important system parameters are listed in the following table.

SYSTEM PARAMETERS

L	$= 215 \times 10^{-3} \text{H}$
R_{circuit}	$= 3 \times 10^{-3} \Omega$ when running
R_{circuit}	$= 263 \times 10^{-3} \Omega$ when dumping
τ_{run}	$= 71.7$ seconds
τ_{dump}	$= 0.82$ seconds

SYSTEM and COMPONENT RATINGS

Magnet I_{max}	$= 4600\text{A}$
Magnet V_{max}	$= 1000\text{V}$ across terminals
Magnet V_{max}	$= 1000\text{V}$ to ground
System I_{max}	$= 3800\text{A}$
System $\int_0^{\infty} I^2 dt$	$= 7$ Mites when quenching
Switch	$= 5000\text{A}$ at 1000VDC
Dump resistor	$= 261 \times 10^{-3} \Omega$, 1400 KJoules

OPERATING PARAMETERS AT 3400A

Stored energy $1/2 LI^2$	$= 1243$ KJoules
$A^2_{\text{sec}}_{\text{coast down}}$	$= 414$ Mites at 3400A
$A^2_{\text{sec}}_{\text{coast down}}$	$= 7$ Mites at 440A
$A^2_{\text{sec}}_{\text{dump}}$	$= 4.7$ Mites at 3400A
$A^2_{\text{sec}}_{\text{dump}}$	$= 5.9$ Mites at 3800A
Dump resistor ΔT	$= 134^{\circ}\text{C}$
Power losses	$= 32.3\text{KW}$
Water flow through bus and switch	$= 6$ GPM at $\Delta P = 80$ PSI

Water ΔT = 17°C

P.S. 480V line current = 150A *

P.S. Power factor = 0.3 *

* Using 500 KW Transrex P.S.

NOTE: 1 Mite = $10^6 \text{A}^2 \text{sec.}$

$$\int_0^{\infty} I^2 dt = I^2 \frac{T}{2} \quad \text{A}^2 \text{sec.}$$

3. DESCRIPTION OF SUBSYSTEMS

3.1 Ground Fault Detector

Refer to sheet 2.

All power components are intentionally grounded via 200Ω connected to the midpoint of the dump resistor. This limits the maximum voltage to ground to about 500V during a quench. The 200Ω grounding resistor limits ground fault currents to about 3A. Fault currents should be limited to 20A or less. High ground fault currents can do severe damage.

The power supply and superconducting load operate very close to 0 volt and a passive ground fault protection scheme of a relay and a fuse is therefore not very practical. It would only work during a quench, and not warn us of trouble during normal DC running. It is for this reason that an active ground fault

detector is needed. This detector lifts the whole power system 5VDC away from ground and trips when the leakage current gets too high. The trip action has 100 msec. delay to avoid nuisance trips. A ground fault trip breaks the interlocks and triggers the first fault detector.

3.2 Magnet Quench Imbalance Detector

Refer to sheet 3.

The magnets and some resistors form a Wheatstone bridge. The balance of the bridge is independent of the frequency. There are two identical redundant circuits monitoring the bridge imbalance voltage. The bridge is normally balanced, except during a quench, when the two magnet legs develop unequal voltages. Both redundant circuits should trip when the imbalance exceeds a preset level. This trip will fire the dump SCR and start a sequence of events indicated on sheet 29. A redundant circuit failure detector, (sheet 13) monitors if both redundant circuits did send a dump pulse.

An intentional offset voltage of 0.5 VDC is constantly added to the bridge imbalance voltage. Both input amplifiers 3650 must therefore work properly. The circuit must remain connected. Disconnecting wires in the bridge circuit will result in a trip.

The bridge circuit on sheet 3 shows further that the imbalance bridge includes both leads. Unequal lead voltages in excess of the imbalance trip setting, will also start a dump fire sequence. This is used for redundancy of the lead voltage detectors.

3.3 Run SCR Gate Control

Refer to sheet 4.

The run SCR's S_1 and S_2 are turned on via a simple DC gate drive circuit as shown on sheet 4.

Both the "dump" SCR S_Q and the "gate negative clamp" SCR S_4 are simultaneously fired from the quench imbalance detector. The gate of S_Q is turned on very hard ($I_{gate} > 1A$ in $< 1\mu sec$) to allow for high di/dt operation. S_Q has a non repetative di/dt rating of $800A/\mu sec.$, with such a gate pulse. Two soaking reactors (sheet 28) of $5 \times 10^{-6}H$ each are used to limit the rate of current rise in S_Q to about $50A/\mu sec$. This is conservative indeed. One reactor would have been enough, but our eager technicians installed two. SCR S_4 keeps the run SCR gates a few volts negative for a period of 5 seconds after a dump pulse. This

enhances the turn-off time and assures that noise will not turn these SCR's on while blocking the quench voltage.

3.4 Lead Overvoltage Protection

Refer to sheet 5.

The lead overvoltage detectors for lead "A" and lead "B" are identical. The lead voltage is sensed at amplifier 3650, rectified at 558 and summed with the transducer output voltage at 3510BM. This sum is then compared with a preset reference at 3510BM and results in a drop out of K_1 if the preset limits are exceeded. Another way of looking at this circuit is to say that the lead voltage is compared to a reference which increases proportional to the load current. The larger the load current is, the larger a lead voltage permitted. The reasoning behind this is as follows:

1. The lead resistance is a function of its temperature. A cold lead has typically a resistance of $10^{-5} \Omega$.
2. The lead voltage detector is in principle a lead over temperature detector.
3. Light load currents in a hot lead can cause just as much voltage drop as high currents in a cold lead.
4. We want to limit the lead temperature under load, and can therefore permit more lead voltage drop at high load currents.

Looking some more at sheet 5 we see that the lead voltage is compared to a positive as well as a negative reference. This turns the circuit into a window comparator that moves up and down with the load current. Lead voltages outside the window result in a trip. Eliminating (disconnecting) the lead will cause a trip above 2000A load. The same is true for disconnecting the transducer. The system will not trip if both are disconnected at the same time.

3.5 Dump Charge Control

Refer to sheets 6, 30.

The charge stored in dump capacitors C_1 and C_2 applies a reverse bias at S_1 and S_2 when S_0 is switched on. This stored charge is more than sufficient to hold this reverse bias long enough to turn S_1 and S_2 off when their firing signal is removed at the same time. The switch is now open and the magnet current has to decay through the dump resistor.

The following happens at the start of a dump pulse:

1. The AC charging supply for the dump capacitors is interrupted for 10 sec. starting at the beginning of a dump pulse.
2. C_1 and C_2 charge up in reverse to a value $I_{\text{magnet}} \times R_{\text{dump}}$. The two $1K\Omega$, 50 watt resistors limit the current through D_1 and D_2 .
3. Both relays K_1 drop.
4. After a few seconds everything is over. Currents through S_Q die out to zero and S_Q starts to block again. C_1 and C_2 charge again when the AC supply comes on at the end of the 10 second off period.
5. Interlock permits are presented as soon as there is sufficient charge in C_1 and C_2 to handle the next dump.

Capacitors C_1 and C_2 are equipped with over pressure interlocks. Failing capacitors develop internal gas pressure and keep the system tripped off. The capacitors are rated to handle 1800VDC in this type of application and failure is very unlikely. The stored turn-off charge in C_1 and C_2 at 380VDC, with the quench switch running at 5000ADC, is about 3.4 times as large as required for a successful dump.

3.6 Interlocks

Refer to sheets 7, 30

Interlocks are presented to two 12 channel interlock cards and summed up. This sum permit is wired to the external interlock of the magnet power supply. Each control module and multiconductor cable carries a set of interlocks at different pins. Unplugging modules and cables or insertion at the wrong spot will result in a trip. The relay rack door is interlocked.

Local indicating lights tell which item tripped. Most interlocks also have a remote status wired to a terminal block which can be connected to the computer readout system. Breaking the interlocks will trip the magnet power supply, fire the dump

SCR and trigger the first fault detector. Several spare interlocks are available for future expansion.

Interlocks are reset via the power supply computer reset function.

3.7 First Fault Detector

Refer to sheets 1, 30.

There are two 8 channel first fault detectors. When the quench switch trips several things happen in rapid succession and it will not be possible to determine the initial cause from the interlock status lights.

Each 8 channel first fault detector registers the first item that tripped and also provides remote status for this. The trip information is presented to the first fault detectors via pulse transformers installed at the monitors and detectors. A number of interlocks are lumped together under the title "Interlock and Emergency Dump". The first fault detector is reset via the power supply "reset" command.

3.8 Heater Control

Refer to sheets 9, 10, 11, 12.

Each magnet has two built in heaters. Firing one heater makes a whole magnet coil go normal and this safely distributes the internally dissipated stored energy, if a dump failure occurs.

Magnet failure can occur when the system $\int_0^{\infty} I^2 dt$ exceeds 7 Mites during a quench and a dump failure. 7 Mites is the equivalent of an operating current of 440 Amp. The heater back up system is therefore set to become active above 400A. The heater firing timing circuit is started by the dump pulse and cancelled by a voltage developed across the dump resistor as a result of a successful dump. Heaters are used for back up protection and are only fired when a dump failure occurs above 400 Amp operating current.

The heaters are supplied from stored energy in capacitors. The heater power supplies are mounted in groups of four channels in one chassis. Each channel is connected to one magnet heater. The amount of charge in each channel is constantly monitored. Unequal discharge, which could result from an open heater or electronic failure, is also watched. Unused channels are therefore discharged in a resistor. Relay K_1 (sheet 12) will automatically pick up when all four channels are charged.

Unequal discharge means that something has failed, that needs to be repaired. These failures can, therefore, only be reset locally, at the heater power supply chassis.

Heater charging is interrupted for ten seconds after a firing pulse. This is sufficient time for the heater current to decay to 0 so that the discharge SCR will regain blocking control. These heater power supplies are similar to the units used for superconducting magnets in the Main Ring. The heater failure monitoring control is different, in order to make it compatible with this system.

3.9 Redundant Failure Detector

Refer to sheet 13.

This circuit monitors whether both magnet imbalance detectors provide an output pulse to the dump SCR. A trip will result if only one circuit works. The redundant circuit failure interlock can be reset from remote, but the local fault light has only local reset.

3.10 Control Power

Refer to sheet 14.

All low level control power is mounted in a separate chassis. Each low level power supply is monitored. A power supply failure will result in a trip. The control power chassis also contains two 4.5 AMP.Hour storage batteries, which automatically take over when the AC control power fails. These batteries are only intended to provide power for an orderly shutdown during a control power failure. Storage batteries can supply large amounts of current into a short, which can lead to wiring burning and possible battery rupture. The batteries are therefore fused with a 10 Amp output fuse. A blown fuse will result in a trip.

3.11 Summary

Refer to sheets 1, 15, 29, 30.

Practically all controls are mounted in single width NIM modules which fit into a crate. This crate and all the other chassis are mounted in a relay rack, where they are interconnected with each other. Sheet 29 shows the interlock and trip flow

diagram better than I can describe it. Sheet 30 shows where we can connect for remote monitoring.

4. PERSONNEL SAFETY

"Caution Charged Capacitors are Part of this Installation"

These yellow warning signs are attached to various parts of this system. There are four possible electrical hazards:

1. Lethal amount of stored energy in capacitors.
2. Momentary (few seconds) high voltages (order of 1000V) developed during a quench.
3. AC line voltages (~~30~~, 480VAC and 120VAC) required for operation.
4. Standby battery in control power chassis.

The fact that the system normally operates at a few volts D.C. must not give a person a false sense of safety.

Only persons familiar with the equipment should attempt repairs.

The following procedures must be used for major repairs:

1. Lock and tag 480VAC at magnet power supply.
2. Lock and tag 120VAC at relay rack.
3. Connect a ground stick to the dump capacitor and short the dump capacitors.
4. Short the heater supply.

5. Install plug lock, T & B # NA-1160, at dump and heater power supply A.C. cord.

NOTE: The low voltage (up to 24 VDC) control power stays on! All equipment in the relay rack is properly shielded, interlocked and safety grounded to make it electrically as safe as practical.

The schematics must be studied to understand this system.

NOTE AGAIN:

THERE ARE TWO PLACES WHERE LOCKS
AND TAGS ARE REQUIRED FOR LOCKOUT.

1. 480 VAC at PS
2. 120 VAC at R.Rack.

Some cryogenic equipment at the magnet leadbox is in close proximity to the magnet power leads. Cryogenic maintenance at the top of the leadbox requires that the power supply 480VAC and the relay rack 120VAC be locked out. The dump capacitor will automatically discharge in 20 seconds when the 120VAC is shut off. The heater capacitors will automatically discharge in 10 minutes. There are no heater connections at the top of the leadbox. The system supervisor must be called if there is any doubt.

5. SYSTEM TRIP SETTINGS

5.1 Magnet Imbalance Detector - (Quench Detector)

Refer to sheet 3 and sheet 9.

The bridge is not symmetrical around a center point. One leg has two magnets and the other has three magnets.

Quench voltages ΔV will present different voltages to the imbalance amplifier A, depending on whether the quench occurs in the "Two Magnet" or "Three Magnet" leg. See figures 1 and 2.

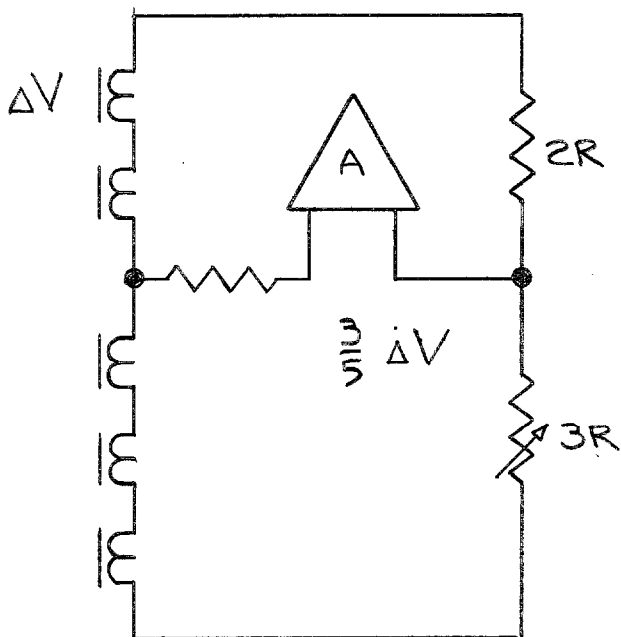


FIG. 1

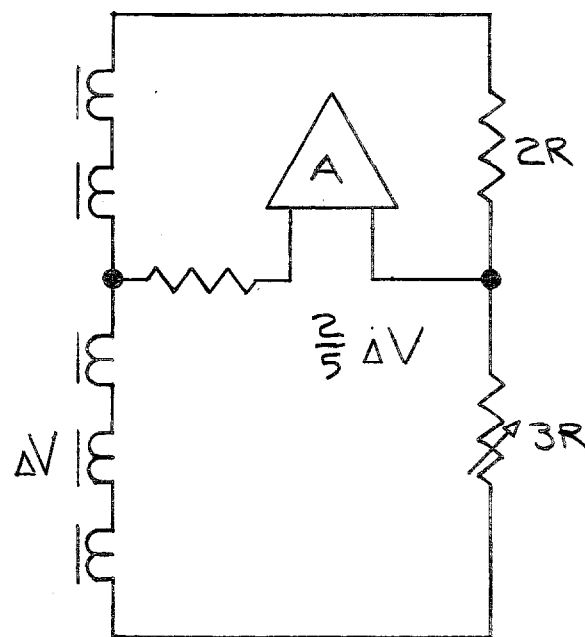


FIG. 2

Imbalance amplifier "A" trips in response to a fixed input voltage.

Record all final trip settings.

Set imbalance detectors as follows:

1. Balance the bridge resistors to a ratio of 2R and 3R. Do this by applying about 10 VAC across the magnet terminals and adjusting R untill 0 volts appears at "A". The 0.5V offset is removed during this adjustment.
2. Introduce 0.50 V offset. Observe +5 volt at output of 3650 (SH 3 - two places). Adjust reference V_B is -5 volt untill the centerpoint of the two 100K Ω resistors at amplifier 3510 BM (SH-3) is at 0 volts. Check four (4) places.
3. Introduce triplevel reference $+V_R = 250\text{mV}$ and $-V_R = 250\text{mV}$ at amplifiers 3510 BM. The outputs of the amplifiers 3510 BM are all high (4 places). K_1 is on.

4. See sheet 9, box #JB 321H. Connect K#LB (clr) in series with V_{test} to TB2/2.* Adjust V_{test} until K_1 drops. Reverse V_{test} and again adjust V_{test} until K_1 drops. K_1 should trip at $V_{test} = (50 \pm 10)mV$. Re-establish circuit.
* Make V_{test} adjustable for convenience.

5. Connect K#LB (Grn) in series with V_{test} to TB 2/6 and adjust V_{test} until K_1 drops. Reverse V_{test} and again adjust V_{test} until K_1 drops. K_1 should trip at $V_{test} = (75 \pm 15)mV$. Re-establish circuit.

Quench trip setting summary:

These settings are such that quench voltages equal to:

ΔV_2 magnet leg = $(50 \pm 10)mV$, or,

ΔV_3 magnet leg = $(75 \pm 15)mV$ will fire the quench switch.

V_R needs to be increased to adjust for higher trip point settings.

After all circuits have been reconnected unplug (SH-9) J_{un} and observe trip.

5.2 Lead Overvoltage.

Refer to sheet 5 and sheet 9.

Record all final trip settings.

1. Set lead "A", no load.

Short the transducer output (sheet 5 at \underline{t} and \underline{r}).
Disconnect lead "A" (sheet 9) at TB 2/3 and apply V_{test} between TB 2/1 and TB 2/3. Adjust V_{test} until K_1 trips.
Reverse V_{test} and again adjust V_{test} until K_1 trips.
Trip points should be at $(20 \pm 2)mVDC$.

2. Set lead "B", no load.

Short the transducer output (sheet 5 at \underline{t} and \underline{r}).
Disconnect lead "B" at (sheet 9) TB 2/5 and apply V_{test} between TB 2/5 and TB 2/7. Adjust V_{test} until K_1 trips.
Reverse V_{test} and again adjust V_{test} until K_1 trips.
Trip points should be at $(20 \pm 2)mVDC$.

3. Set lead "A" with simulated load current.

Apply 10VDC at the transducer output

(sheet 5 at t and r, polarity r positive). Apply $V_{\text{test}} = + 50\text{mVDC}$ between TB 2/1 and TB 2/3. This simulates 5000A operation.

Increase V_{test} to about 70mVDC and observe K_1 trip.

Decrease V_{test} to about 30 mVDC and observe K_1 trip. Set trip points (with 10V transducer voltage!) at $(70 \pm 5)\text{mVDC}$ and $(30 \pm 5)\text{mVDC}$.

Reverse V_{test} and repeat the above procedure.

4. Set lead "B", with simulated load current.

Apply 10VDC at the transducer output (sheet 5 at t and r polarity r positive). Apply $V_{\text{test}} = + 50\text{mVDC}$ between TB 2/5 and TB 2/7. This simulates 5000A operation.

Increase V_{test} to about 70mVDC and observe K_1 trip.

Decrease V_{test} to about 30mVDC and observe K_1 trip.

Set trip points (with 10V transducer voltage!) at $(70 \pm 5)\text{mVDC}$ and $(30 \pm 5)\text{mVDC}$.

Reverse V_{test} and repeat the above procedure.

Lead voltage trip setting summary:

The leads will now cause a trip when:

$$V_{\text{lead}} > [I \times 10^{-2} + (20 \pm 5)] \text{mV},$$

or,

$$V_{\text{lead}} < [I \times 10^{-2} - (20 \pm 5)] \text{mV}$$

I in AMP

The 20mV window can be increased by choosing a larger V_R . Restore all circuits after test.

5.3 Dump Charge

Refer to sheet 6.

Observe K_1 trip at $(375 \pm 25)V$ charge in C_1 and C_2 . Do this by removing the AC feed and letting the capacitors bleed down. Charge the capacitors and observe K_1 pick up at $(375 \pm 25)V$. Adjust as needed.

5.4 Heaters

Refer to sheet 12.

Perform check per sheet 12. Drop out of K_1 must occur at $(400 \pm 20)V$. Test this by removing the AC feed and letting the capacitors bleed down. Check all channels individually. Check heater enable setting above 400A (0.8V from P.S. transducer, sheet 10).

5.5 D.C. Overcurrent

Set the overcurrent trip of the 5000A magnet power supply at 3800 ADC.

5.6 Ground Fault Trip

Refer to sheet 2.

Adjust for a ground fault trip at a leakage resistance to ground of less than $1 K\Omega$. Take the connection at R_D TB1/2 loose. Install $1K\Omega$ to ground and adjust the circuit until K_1 drops. Remove the $1K\Omega$ resistor and K_1 should pick up.

6. FIRST START UP and SYSTEM CHECKS

6.1 Wiring

Each subassembly must be (was already) tested for correct wiring and performance. Check all interconnecting field wiring per sheets 23, 24, 25, 26.

6.2 Megger

Megger test system to ground at 500VDC.

6.3 System Tests

Sheet 29 is a system interlock control "road map". Check all items on this sheet by putting a check mark at each item that was checked.

Check List

1. Check all interlocks.
2. Run SCR timing and gate voltage. (reference sheet 4).
3. Dump charge timing control.
4. Heater control and timing. Simulate conditions shown on sheet 29. Dump the heaters temporarily in resistors.

5. Emergency dump.
6. Multibus interrupt.
7. Dump SCR gate voltage and current pulse. (Reference sheet 4).
8. Control power failure.
9. First fault detector and status.
10. Water on.
11. Power supply.
12. Power connections.
13. Test all trip settings

After all preliminary checks are made and all wires reconnected the system is ready for turn on at low power.

6.4 Start Low Current Run

Turn power supply on. Set I = 400A

Check List

1. Power supply regulation and output voltage. (Use a scope to check for 12 phase output)

2. Simulate an emergency quench. Did it work?
3. Remove the heater control input from the dump resistor and push the heater required button. Start up to $I = 400A$. Enter the tunnel. Did the system dump? The heaters should have fired.
4. Reconnect the heater control at the dump resistor.
5. Simulate a dump failure by removing S_Q gate. Run the system at $400A$ and simulate an emergency quench. The heaters should fire. Restore S_Q gate.
6. Restart and gradually increase the load current to the required running current of about $3000ADC$.
7. Measure S_1 , S_2 forward drop at $1000A$. (Refer to sheet 28).

7. DESIGN CALCULATIONS

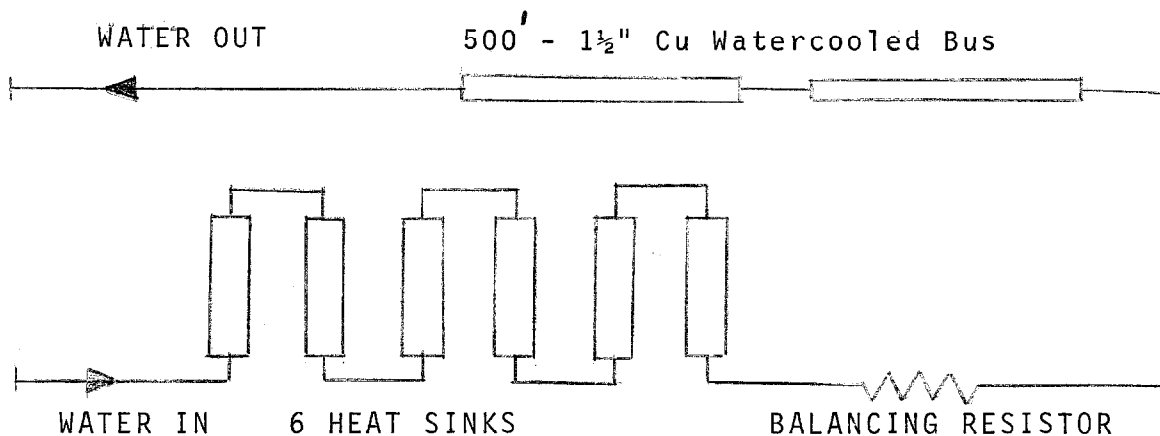
The number of magnets in the string was increased from four (4) to five (5) during the design of this system and after the dump resistor was built. This change did not effect the ratings of the power components.

The calculations for the dump resistor are based on the old system of four (4) magnets running at 3400ADC, but this resistor is also adequate for the five (5) magnet string. Other design parameters are simply chosen to take care of any other quench switch application in the experimental area's running at less than 5000ADC with a maximum quench voltage of 1000V.

A different dump resistor needs to be designed for each application that is substantially different in operating current and stored energy.

7.1 5000A Quench Switch Cooling Flow Estimates

Run all heat sinks, the balancing resistors and all watercooled bus in series for cooling.



The losses at 4600A are:

6 sinks (2 SCR's)	4.6 KW
Bal. Resistors	5.3 KW
500 Ft. of bus at $4.5 \times 10^{-3} \Omega / 1000 \text{ ft.}$	47.6 KW
TOTAL LOSSES	57.5 KW

Allow ΔT water out = 30°C

The required flow is then:

$$\text{GPM} = \frac{\text{KW} \times 3.2}{\Delta T} = \frac{57.5 \times 3.2}{30} = 6.2 \text{ GPM}$$

7.2 Calculate the Run SCR Operating Temperature

Run SCR's and S_1 and S_2 , GE # C782PNV701.
The allowable junction operating temperature is 125°C .
The SCR forward drop is 1.5V at 2500A.

Thermal impedances with double side cooling are:

SCR junction to case- $R_{\theta JC} = 0.012$ $^{\circ}\text{C/Watt}$

SCR case to sink - $R_{\theta CS} = 0.005$ $^{\circ}\text{C/Watt}$

Sink to water at 1GPM- $R_{\theta SW} = 0.0045$ $^{\circ}\text{C/Watt}$

Total Junction to Water: $R_{\theta JW} = 0.0215$ $^{\circ}\text{C/Watt}$

Each SCR loss at 2500A is: $1.5 \times 2500 = 3750$ Watt

The SCR junction temperature rise equals:	0.0215×3750	=	80.6	$^{\circ}\text{C}$
Maximum inlet water temperature:		=	40.0	$^{\circ}\text{C}$
The water temperature rise for losses in the first SCR is:	$\frac{3.75 \times 3.2}{6}$	=	2.0	$^{\circ}\text{C}$

The maximum junction temperature of the run SCR at 5000A operating current is:

123.0 $^{\circ}\text{C}$

CONCLUSION: This switch can handle 5000ADC.

7.3 Calculate the Heat Sink Temperature

The maximum temperature is:

$$3750 \times 0.0045 + 40 + = 59^{\circ}\text{C}$$

Use 80°C klixons for overtemperature (loss of flow protection) at the SCR sinks.

7.4 Calculate the Cooling Flow Pressure Drop

Estimate the pressure drop as follows:

500'	of bus, 1.1" ID, at 6.2 GPM	=	4.5	PSI
20'	of 3/8" hose and balancing			
	resistor at 6 GPM	=	44	PSI
6	Sinks at 6 GPM		36	PSI (estimate)
			<hr/>	
Required total ΔP		=	85	PSI

NOTE: Check water flow before start up.

CONCLUSION: This amount of cooling seems adequate and matches the available site ΔP of 80 PSI.

7.5 Calculate the Dump SCR Operating Temperature

The dump SCR, Westinghouse #TA201016, rated for 125°C operating temperature, is normally off and sits at 40°C maximum at the start of a dump.

The resonant frequency of the dump capacitor and the load (5 magnets) is:

$$f = \frac{1}{2\pi \sqrt{LC}}$$

$$f = \frac{1}{2\pi \sqrt{5 \times 0.043 \times 4460 \times 10^{-6}}}$$

$$\begin{aligned} f &= 5.14 \text{ Hz} \\ T &= 0.194 \text{ sec.} \end{aligned}$$

The worst dump SCR current pulse looks like figure 7.5.1, which, for transient heat calculations, can be replaced with a pulse as in figure 7.5.2.

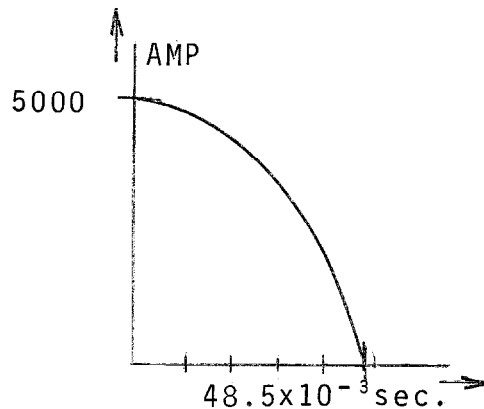


Figure 7.5.1

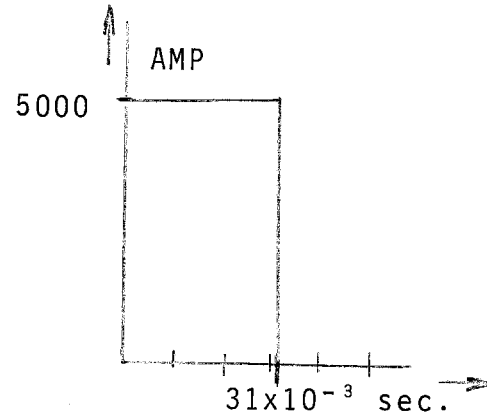


Figure 7.5.2

Dump SCR current pulse.

The DC transient thermal impedance of the dump SCR #TA201016 at 31×10^{-3} sec. is $\theta_{JC} = 0.0035^{\circ}\text{C/watt}$ and the SCR forward drop is 1.7 volts at 5000A, which equals 8500 watt loss at that current.

The SCR temperature rise is therefore:

$$8500 \times 0.0035 = 30^{\circ}\text{C}.$$

The dump SCR is thus way too big for this application, but the chosen SCR requires 8000 pounds mounting force, which makes packaging much easier and more economical. The run SCR's require the same mounting pressure.

7.6 Calculate the Dump Diode Operating Temperature

The dump diode Westinghouse #RA201025 has a rated junction operating temperature of 190°C . This diode is normally off and sits at 40°C maximum at the start of a dump.

The magnet current decays with the circuit $L/R = 0.82$ sec. time constant.

The worst current pulse through the diode looks like figure 7.6.1 and can be replaced with a pulse as in figure 7.6.2 for diode temperature rise calculations.

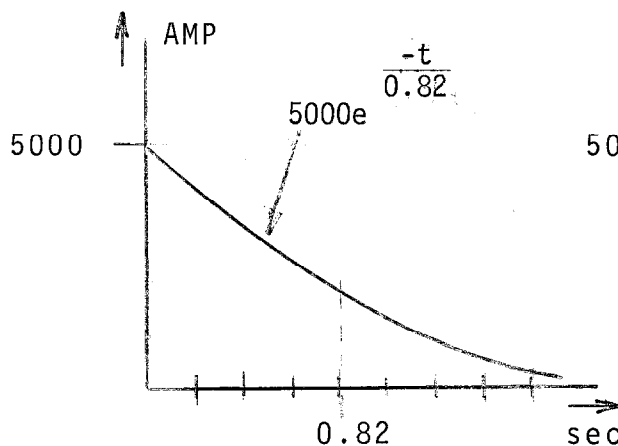


Figure 7.6.1

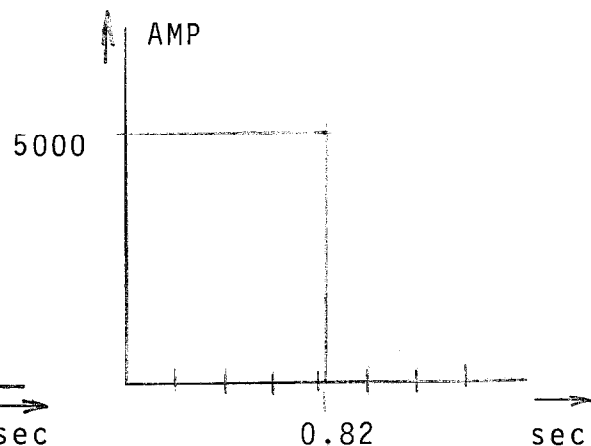


Figure 7.6.2

Current pulse through dump diode.

The transient thermal impedance of the diode is $\theta_{JC} = 0.008^{\circ}\text{C/watt}$ at 0.82 sec. and the diode forward drop is about 1.1 volt at 5000A, which equals 5500 watt loss at that point.

The diode temperature rise is therefore:

$$5500 \times 0.008 = 44^{\circ}\text{C}$$

The dump diode is way too big for this application. This diode is chosen because it requires 8000 pounds mounting force which makes packaging much easier and more economical.

7.7 Calculate the Size of the Dump Capacitor

(Ref. TM 962-6065-000)

Let C be the size of the dump capacitor, charged at dV volt while the system operates at i Amp. C has to be able to supply i Amp for a duration of t_q seconds.

Thus:

$$C = i t_q / dV$$

t_q = turn off time of SCR GE # 782PNV701

$$t_q = 100 \times 10^{-6} \text{ sec.}$$

Charge voltage select :

$$dV = 380V$$

$$C \geq \frac{5000 \times 100 \times 10^{-6}}{380} \text{ F}$$

$$C \geq 1315.8 \text{ } \mu\text{F}$$

Choose

$$C = 2 \times 2232 = 4464 \text{ } \mu\text{F}, 1800V \text{ max.}$$

Charge safety factor 3.4

This will take care of variations in the SCR turn of time. A safety factor of 2.5 would have been enough. $C = 2232 \text{ } \mu\text{F}$ is available in a standard commercial capacitor (catalogue item).

7.8 Design Current Balancing (Sharing) Resistors for 2-2500A SCR's in Parallel

$$\text{Required } R = 0.5 \times 10^{-3} \Omega$$

Make R from 304 watercooled stainless steel tube.

304 Stainless Steel Properties

Spec. weight	$w = 8.03 \times 10^{-3} \text{ kg/cm}^3$
Spec. heat	$c = 502.38 \text{ Joules/}^\circ\text{Ckg}$
Spec. resistivity at 20°C	$\int_{20} = 72 \times 10^{-6} \Omega \text{ cm}$

Spec.resistivity at 70°C $\rho_{70} = 75.5 \times 10^{-6} \Omega \text{ cm}$
Temp.Coeff.of resistivity $\alpha = 9.71 \times 10^{-4} \text{ per } ^\circ\text{C}$

Choose:

5/8", 11 gage 304 stainless steel tube.

Area of Cross Section = A

$$A = \frac{\pi}{4} (\phi_{\text{outer}} - \phi_{\text{inner}}) (\phi_{\text{outer}} + \phi_{\text{inner}}) = \frac{\pi}{4} (2.54^2 - 1.315^2)$$

$$A = 1.228 \text{ cm}^2$$

$R_{2\phi}$ of 1 cm long pipe = $R_{2\phi}/\text{cm}$

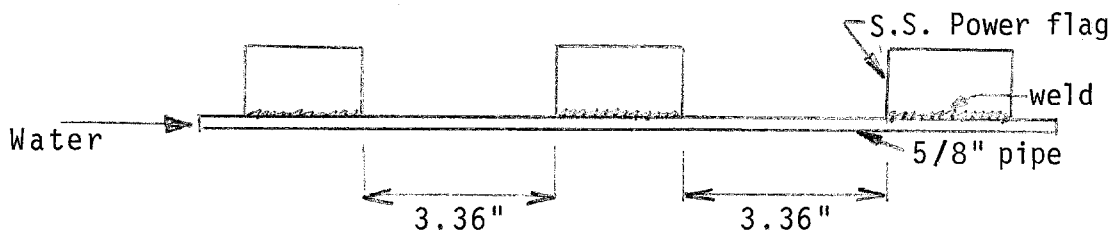
$$R_{2\phi} = 58.62 \times 10^{-6} \Omega/\text{cm}$$

For $0.5 \times 10^{-3} \Omega$ we need length L

$$L = \frac{0.5 \times 10^{-3}}{58.62 \times 10^{-6}} = 8.52 \text{ cm (3.36 inches)}$$

Sharing resistor losses at 5000A are:

$$2 \times (2500)^2 \times 0.5 \times 10^{-3} \times 10^{-3} = 6.25 \text{ k Watt.}$$



7.9 Dump SCR di/dt Considerations

Dump SCR type Westinghouse #TA 2010-16

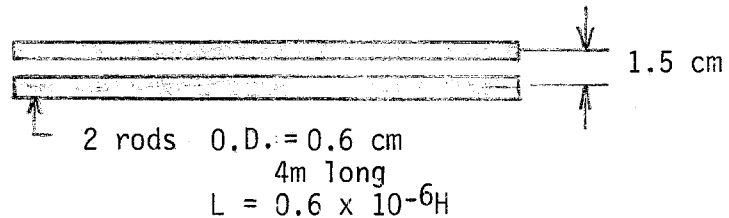
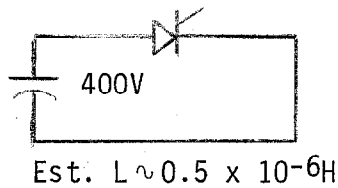
Ratings: $V_{\text{DRM}} = 1000\text{V}$

$I_{\text{TAV}} = 1600\text{A}$

$$I_{GT} = 200\text{mA}$$

Non repetative $di/dt = 800\text{A}/\mu\text{sec.}$ for $3 \times I_{GT}$ in $1 \mu\text{sec.}$

Estimate L of Discharge Circuit



It is hard to make this type of circuit with less than $0.5 \times 10^{-6}\text{H}$.

$$V = L di/dt$$

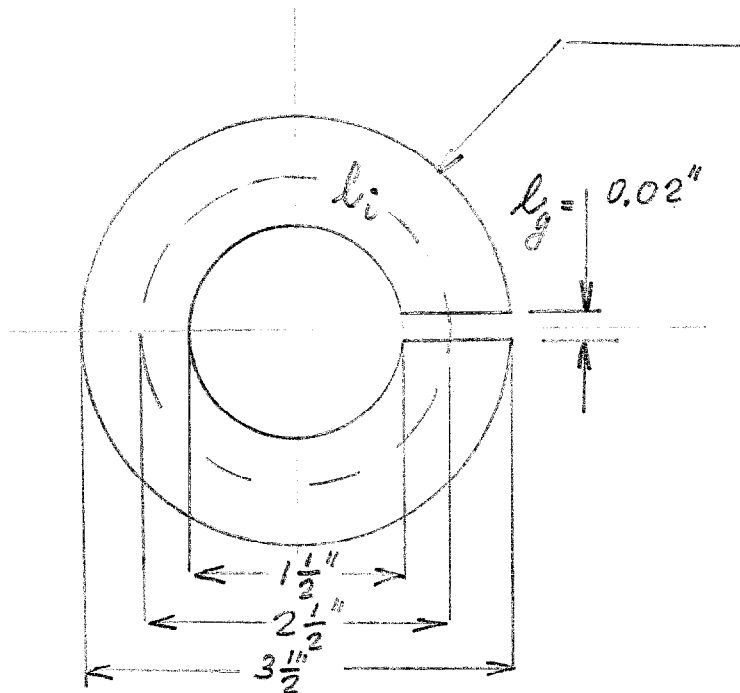
$$di/dt = 400/0.5 \times 10^{-6} = 800\text{A}/\mu\text{sec.}$$

I feel that this di/dt estimate is very pessimistic but we could employ a soaking reactor to be safe.

7.10 Design of the Soaking Reactor to Limit
Dump SCR $di/dt < 200\text{A}/\mu\text{sec.}$

Make the soaking reactor from a tape wound silectron core, of 4 mil thick steel. Put it around the discharge cable. The remanent field of an uncut core is about 14 kGauss. The discharge current flows always in the same direction. We need to make a 20 mill (practical size) cut in the core, to get the remanent field down.

Estimate the core to look like:



Tape wound silectron
steel core with airgap.

l_i = average iron length

l_g = gap height

$$\frac{l_i}{l_g} = \frac{\pi \times 2.5}{0.02} = 392$$

What is the remanent field now?

Ref. TM-978-6013-000

$$B_r = \frac{4\pi \times 10^{-7} H_c \frac{l_i}{l_g} \times 10^4}{\frac{l_i}{\mu_r l_g} + 1} \text{ Gauss (7.10.1)}$$

(H_c in AT/m)

Estimate $\mu_r = 2 \times 10^4$

4 mil silectron $H_c \approx 0.5$ Oersted (40 AT/m)

The above values can be obtained from steel curves.

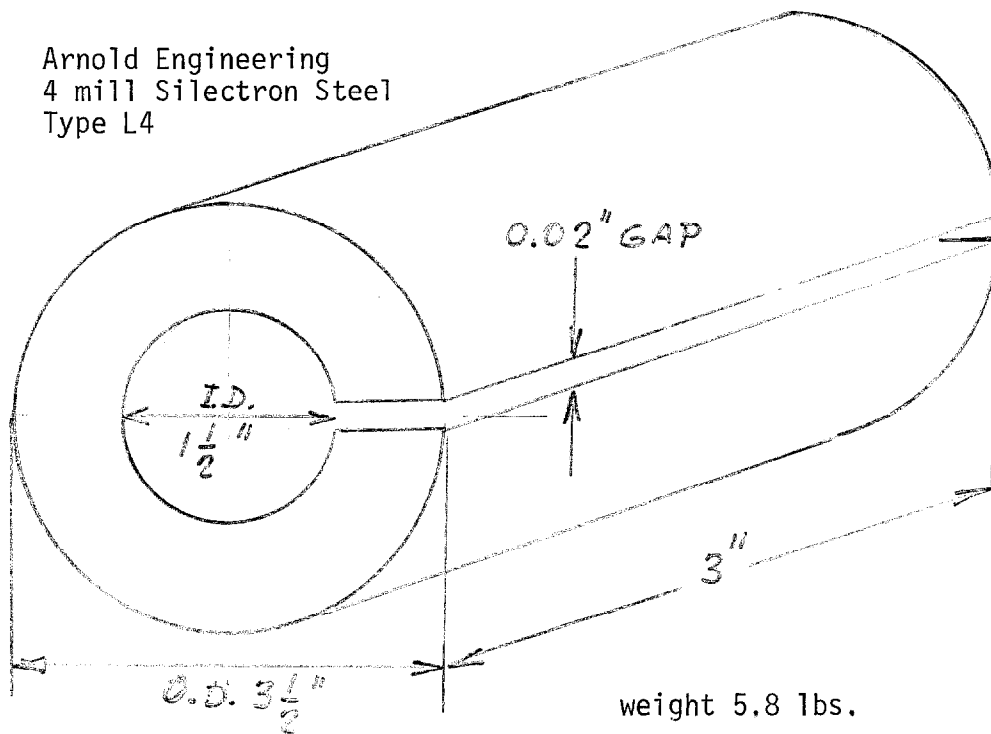
TM-1177
2700.000

Filling out the applicable values
in equation 7.10.1 we find:

$$B_r = 193 \text{ Gauss}$$

Thus a 10 to 20 mil gap is reasonable!

Make the reactor as below:



The inductance of this core is a function of the operating current and is calculated here after.

$$Ni = \oint H \, dl$$

$$Ni = \frac{B_i}{\mu_o \mu_r} l_i + \frac{B_{gap}}{\mu_o} l_g \quad N = 1$$

$$l_i = \pi \times 2.5 \times 2.54 \times 10^{-2} = 20 \times 10^{-2} \text{ meter}$$

$$l_g = 20/10000 \times 2.54 \times 10^{-2} = 5 \times 10^{-4} \text{ meter}$$

$$Ni = Ni_{iron} + Ni_{air}$$

$$Ni = Ni_{iron} + \frac{B_g}{4\pi \times 10^{-7}} \quad 5 \times 10^{-4}$$

$$Ni = H_{Bi} \times 80 \times 20 \times 10^{-2} + 400 B_g$$

$$H_{Bi} \text{ in Oersted to be determined from B-H curve.}$$

(1 Oersted = 80 AT/m)

$$B_g \text{ in WB/m}^2$$

(1 WB/m² = 10 k Gauss)

$$Ni = 16 H_{Bi} + 0.04 B_g \text{ Amp. turns.}$$

$$H_{Bi} \text{ in Oersted}$$

$$B_g \text{ in Gauss}$$

From the reactor size we can calculate the flux ϕ .

$$\phi = B \times 3 \times 2.54 \times 1 \times 2.54 \times 10^{-4} \times 10^{-4}$$

$$\phi = 19.4 B \times 10^{-8} \text{ Weber}$$

$$B \text{ in Gauss}$$

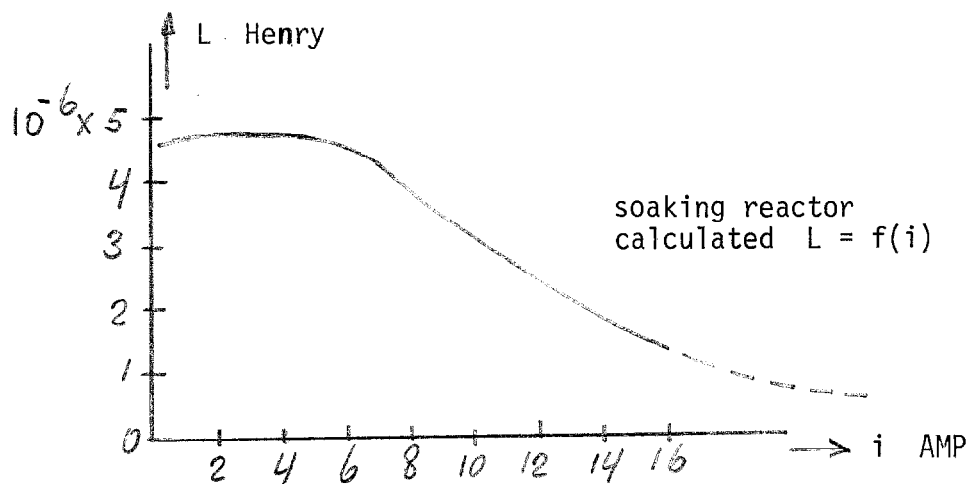
The reactor inductance L is:

$$L = \frac{N\phi}{i} \text{ Henry}$$

Make the following table:

N=1					
B	Ni	Ni	ϕ	i	L
KG	IRON	AIR	WEBER	AMP	HENRY
2	5	80	3.9×10^{-4}	85	4.6×10^{-6}
4	5.6	160	7.8×10^{-4}	166	4.7×10^{-6}
8	8	320	15.5×10^{-4}	328	4.7×10^{-6}
12	14.4	480	23.3×10^{-4}	495	4.7×10^{-6}
16	80	640	31.0×10^{-4}	720	4.3×10^{-6}
20	1600?	800	38.8×10^{-4}	2400	1.6×10^{-6}

From this table we can make a plot, which shows the soaking reactor inductance as a function of the current.



This looks like a reasonable reactor. This soaking reactor will limit the di/dt to:

$$\frac{di}{dt} = \frac{\text{Charge voltage}}{\text{Circuit inductance}}$$

Choosing a charge voltage of 400V, a soaking reactor of $4.7 \times 10^{-6} \text{ H}$ and an estimated circuit lead inductance of $0.3 \times 10^{-6} \text{ H}$ we find:

$$\frac{di}{dt} \approx 80 \frac{A}{\mu\text{sec}}$$

This is well within the equipment ratings.

7.11 Design of the Dump Resistor for Enclosure "H"

Ref. TM-962-60650-000

The dump resistor must be able to dissipate the stored energy in the system, without getting too hot. The ohmic value is limited by the maximum permissible magnet voltage.

Suppose that at some time we want to operate at 4000A through four E.D. dipoles in series, then we find:

$$R_D = 1000/4000 = 0.25\Omega \text{ max.}$$

$$\frac{1}{2} Li^2 = 4 \times \frac{1}{2} \times 0.043 \times 4000^2 = 1376 \times 10^3 \text{ Joules}$$

$$\text{Allow: } \Delta T = 160^\circ\text{C} (200^\circ\text{C maximum temperature at } R_D)$$

If ΔT is the permissible temperature rise of the steel in $^\circ\text{C}$, then we find for the weight W:

$$W = \frac{\frac{1}{2} Li^2}{c\Delta T} \text{ kg}$$

$\frac{1}{2} Li^2$ - Stored energy in Joules

c - Specific heat of steel in Joules/ $^\circ\text{C}$ kg (c \approx 500)

ΔT - Temperature rise in $^\circ\text{C}$

The required weight of the steel is:

$$\frac{1376 \times 10^3}{500 \times 160} = 17.2 \text{ kg} \quad (38 \text{ lbs})$$

Thus: We need to find a length of 304 stainless steel that weighs 38 lbs. and has 0.25 Ω resistance

The specific resistance of 304 stainless steel is:

$$\rho_{20} = 72 \times 10^{-6} \Omega \text{cm}$$

Choose to make the dump resistor from 1/8" x 1" stainless steel strap.

$$\text{Cross section: } 1/8 \times 1 \times 2.54^2 = 0.8064 \text{ cm}^2$$

$$\text{Resistance: } \frac{72 \times 10^{-6}}{0.8064} \times 2.54 \times 12 = 2.72 \times 10^{-3} \Omega/\text{ft.}$$

$$\text{Weight: } 0.425 \text{ lbs/ft.}$$

$$\text{Needed length } L \text{ for } 250 \times 10^{-3} \Omega \text{ is:}$$

$$L = 250/2.72 = 91.9 \text{ ft. and weighs } 39.6 \text{ lbs.}$$

This is an adequate amount of steel. Buy the stainless steel strap in 20 ft. lengths and fold it back and forth, so that the total resistor length is about four feet. Weld the joints and use teflon spacers for separators.

Using multiples of 4 ft. strap length yields a final dump resistor as follows:

$$R = 261 \times 10^{-3} \Omega$$

$$W = 40.8 \text{ lbs.}$$

$$P = 1400 \text{ K Joules}$$

$$\Delta T = 151^\circ \text{C}$$

$$V = 1044 \text{ volt at } 4000 \text{ A.}$$

A dump resistor of $261 \times 10^{-3} \Omega$ limits the $A^2 \text{sec}_{\text{dump}}$ to 5.9 Mites (5 magnets at 3800A) which is less than the permissible value of 7 Mites.

8. MATERIAL COST ESTIMATE

Some materials for the quench switch were obtained from surplus, others from Fermi stock. Most power components were purchased in lots for five quench switches.

The following table shows a breakdown of the estimated equipment cost for one complete quench switch.

COST ESTIMATE-5000A QUENCH SWITCH

1. Crate with electronics		\$2000
2. Heater Power Supply - 2 PCS		2000
3. Control Power Chassis and Standby Power		500
4. Miscellaneous parts, wires R. R. doors etc.		1000
5. Quench Switch Assembly		
2 Capacitors	\$1800	
3 SCR's	1400	
1 Diode	155	
6 Sinks	408	
2 Clamps	220	
1 Dump resistor	200	
1 Balance resistor	100	
1 Soaking reactor	26	
Miscellaneous	200	
		<hr/> 4500
Total Estimate		<hr/> \$10,000
material for one quench switch		

9. ACKNOWLEDGEMENTS

A system is never any better than the technicians who put it together. I think they did a marvelous job and I like to give them credit for this.

The following persons worked on this project and they will also be involved with the construction of the next ten (10) switches.

M. Herren	:	Logic design, layout and assembly.
R. Innes	:	General supervision, packaging, design.
D. Jakubek	:	Component layout, assembly.
W. Jaskierny	:	Control power design, assembly.
R. Moore	:	Assembly.
F. Rittgarn	:	Field Installation.

The Cryogenic steering committee, chaired by Roger Dixon, offered many suggestions. I did not always agree with their requirements. However, a large number of their comments were very useful and led to a better understanding.

10. REFERENCES

1. UPC - 155, Doubler System Quench Threshold - K. Koepke and P. Martin, January 25, 1982.
2. TM-1134/1790.00, Energy Saver A-Sector Power Test Results - P. Martin, R. Flora, G. Tool and D. Wolff, September 15, 1982.
3. TM-962/6065.00, Electrical Protection of Low-Current Superconducting Magnet, A.T. Visser, April 25, 1980.
4. TM-835/2822.000, Meson Superconducting Magnet Energy Dump System, J.B. Stoffel, December, 1978.
5. TM-978/6013.000, A Short Approach to the Electrical Design of a Muon Spoiler Magnet, A.T. Visser.